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MEMORANDUM REPORT NO. 1410
JUNE 1962

SURFACE AIR BLAST MEASUREMENTS FROM A 100-TON TNT DETONATION

C. N. Kingery
J. H. Keefer
J. D. Day

BALLISTIC RESEARCH LABORATORIES

ABERDEEN PROVING GROUND, MARYLAND

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Terminal Ballistics Laboratory

Program was supported in part by
the Defense Atomic Support Agency; WEB No. 02.043

ABERDEEN PROVING GROUND, MARYLAND

B A L L I S T I C   R E S E A R C H   L A B O R A T O R I E S

MEMORANDUM REPORT NO. 1410

CNKingery/JHKeefer/JDDAY/iv
Aberdeen Proving Ground, Md.
June 1962

SURFACE AIR BLAST MEASUREMENTS FROM A 100-TON TNT DETONATION

ABSTRACT

This report presents the free field pressure-time histories measured at selected distances from a 100-ton TNT surface burst. Included in the presentation are plots of overpressure, duration, impulse, arrival time, and dynamic pressure all - versus distance. The measured values are compared with predicted curves which were prepared by scaling results from 5-ton and 20-ton surface bursts of the same geometrical shape and fired in the same general area. The geometrical shape is a simulated hemisphere which was constructed by stacking cast TNT blocks in a planned pattern.

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LIST OF SYMBOLS

q = dynamic air pressure

M = local free stream Mach number of flow behind blast front

P_t = free stream total pressure (absolute)

P_p = total head pitot pressure (absolute)

P_s = free stream static pressure (absolute)

P_o = ambient pre-shock static pressure

γ = ratio of specific heats

ΔP = free stream static overpressure

ΔP_p = total head pitot overpressure

Primes are used to denote uncorrrected, "as read" gage values.

INTRODUCTION

1.1 Objectives

There were many projects participating in the 1961 Canadian 100-ton TNT trial but a relatively small number recorded the free-field parameters associated with the blast wave. The primary objective of this report is to put the free-field measurements made by the U. S. Test Group in a separate report for quick distribution. It is hoped that this might be of some assistance to those projects requiring input conditions in preparing final reports. The records in this report can also be compared with those obtained by the Suffield Experimental Station (SES) along their blast line.

1.2 Background

Members of US Project 15 from the Ballistic Research Laboratories (BRL) have participated in the high explosive tests conducted by SES in 1959, 1960, and 1961. The 1959 test included a 5-ton surface shot, the 1960 test included a 20-ton surface shot, and the 1961 test included a 100-ton surface shot. All of the surface shots were composed of cast TNT blocks manufactured under strict quality control. The standard TNT block size was 12" x 12" x 4" and weighed an average of 32.5 lb. The charges were stacked in layers with each layer decreasing in area to form a hemisphere. Therefore all charges were of the same geometrical shape and fired in the same general area. The predicted curves presented in this report were scaled up from measurements obtained on the 5-ton and 20-ton surface bursts. The measurements include peak overpressures calculated from shock velocity and overpressure versus time from electronic and self-recording gages.

1.3 Meteorological Conditions

Date: 3 August 1961

Time: 1030 MST

Site: Watching Hill Blast Range

Atmospheric Pressure: 13.67 psi

Relative Humidity: 21 percent

Cloud: 8/10 cirrus. Bright sunshine

Vertical wind profile (direction true bearing, speed miles per hour)

Height, meters	0.6	2	4	8	16	32	64	128	256
Position X									
Direction		095							
Speed		3.6	3.8	4.0	4.2	4.4	4.7	5.1	5.5
TPS 7									
Speed	3.0	3.2	3.4	3.6	3.8	4.0	4.3	4.6	5.0
TPS 8									
Direction	090			095					
Speed	7.0	7.6	8.0	8.3	8.7	9.1	9.6	10.0	10.5

Vertical temperature profile, ^{o}F : at O.P.

Height, meters	Surface	0.025	0.5	1.25	4	8	16	32	64	128	256
Temperature	130	104	91	90	88	87	86	85	83	82	80

Position X was toward 095^{o} at 560 from ground zero.

TPS 7 was toward 278^{o} at 1000 feet from ground zero.

TPS 8 was toward 278^{o} at 2000 feet from ground zero.

The Observation Point (O.P.) was toward 240^{o} at 5,050 feet from G.Z.

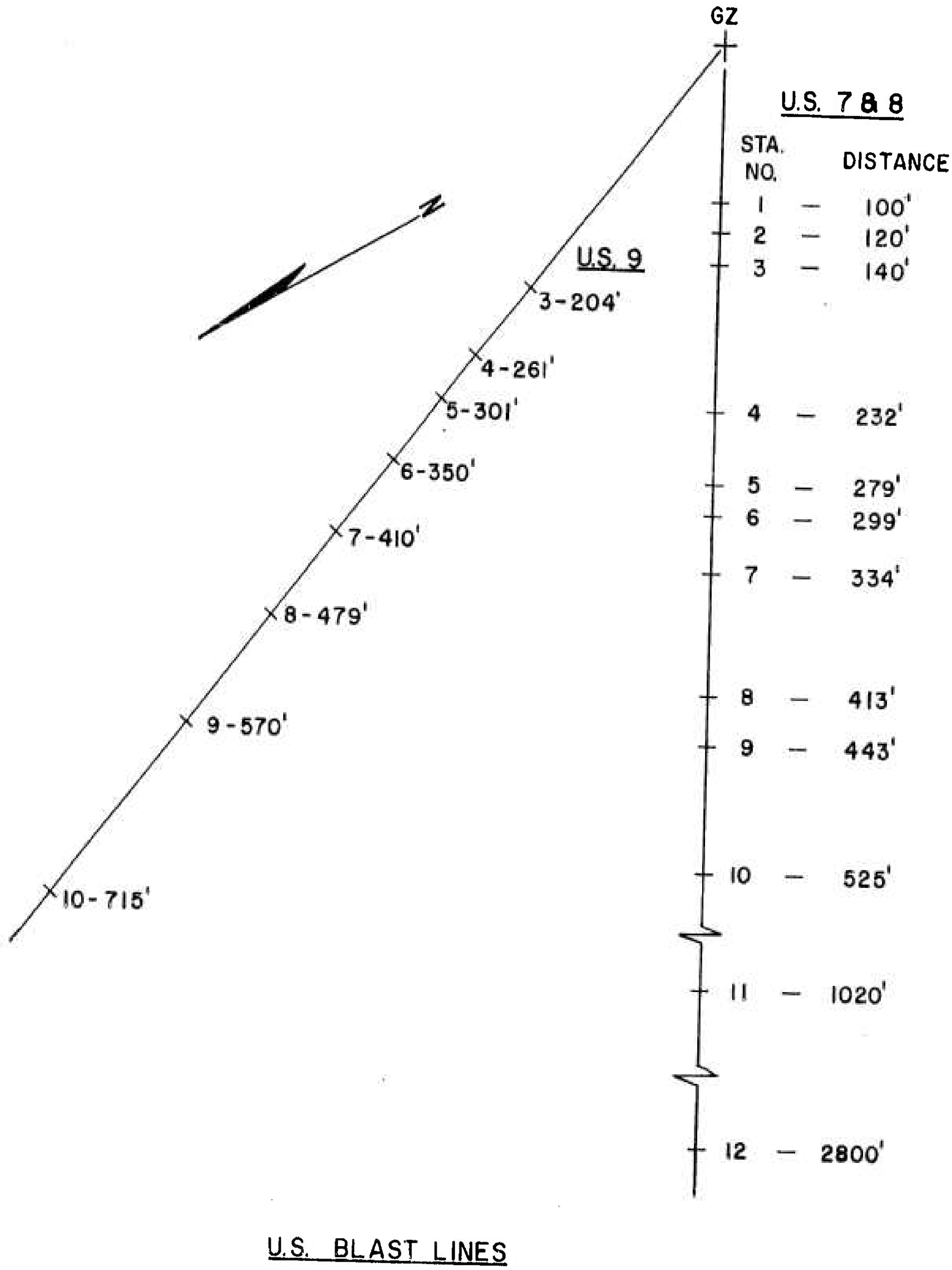

Figure 2.1 Station Locations Along the U. S. Blast Lines

PROCEDURE

2.1 Operations

The majority of the projects associated with the US Test Group were located within a 90-degree sector. Within this sector two main blast lines were established. One line was primarily for US Projects 7 and 8, and ran between the two. The other line was established primarily for US Project 9 but ran between US 8 and 9. The data recorded along the two blast lines should meet the needs of any US projects within the immediate area. The blast line layout is shown in Figure 2.1.

2.2 Instrumentation

The free-field measurements were made using a variety of transducers and recorders. Detailed descriptions of the transducers and recorders will be presented in a final report from US Projects 15a and 15b and will therefore not be discussed in this report. The type transducer and recorder combination is presented in Tables 2.1 and 2.2. All free-field overpressure measurements presented in this report were made with the transducer or pressure inlet hole flush with the ground surface. Gages in the higher pressure regions were mounted in concrete blocks. The total head pressure measurements were made with the probe mounted three feet above the ground surface. A photograph of a typical station is presented in Figure 2.2

TABLE 2.1

Transducer and Recorder Combinations along U.S. Blast Line 7 - 8

Position	Distance from GZ	Transducer	Recorder	Type Measurement
8.1B	100'	Mechanical	Self-Recording	Side-on
8.2	120'	Detroit Control	Miller	Side-on
A		Mechanical	Self-Recording	Side-on
B		Mechanical	Self-Recording	Side-on
8.3A	140'	Mechanical	Self-Recording	Side-on
B		Mechanical	Self-Recording	Side-on
8.4A	232'	Mechanical	Self-Recording	Side-on
8.5	279'	Piezo	Miller	Total
		Piezo	Miller	Side-on
A		Mechanical	Self-Recording	Side-on
8.6	299'	Piezo	Miller	Total
		Piezo	Miller	Side-on
A		Mechanical	Self-Recording	Side-on
8.7	334'	Detroit Control	Leach	Total
		Detroit Control	Leach	Side-on
A		Mechanical	Self-Recording	Side-on
8.8	413'	Detroit Control	Miller	Total
		Detroit Control	Miller	Side-on
A		Mechanical	Self-Recording	Side-on
8.9	433'	Detroit Control	Leach	Total
		" "	Leach	Side-on
A		Mechanical	Self-Recording	Side-on
8.10	525'	Piezo	Miller	Side-on
A		Mechanical	Self-Recording	Side-on
8.11A	1020'	Mechanical	Self-Recording	Side-on
8.12A	2800'	Mechanical	Self-Recording	Side-on

TABLE 2.2

Transducer and Recording Combinations along U. S. Blast Line 9

Position	Distance from GZ	Transducer	Recorder	Type Measurement
9.3	204'	Detroit Control	CEC - 3KC	Side-on
A		Mechanical	Self-Recording	Side-on
B		Mechanical	Self-Recording	Side-on
9.4	261'	Detroit Control	Miller	Total
		Detroit Control	CEC - 3KC	Side-on
A		Mechanical	Self-Recording	Side-on
B		Mechanical	Self-Recording	Side-on
9.5	301'	Detroit Control	CEC - 3KC	Total
		Detroit Control	CEC - 3KC	Side-on
A		Mechanical	Self-Reading	Side-on
9.6	350'	Detroit Control	CEC - 3KC	Side-on
A		Mechanical	Self-Recording	Side-on
B		Mechanical	Self-Recording	Side-on
9.7	410'	Detroit Control	CEC - 3KC	Side-on
A		Mechanical	Self-Recording	Side-on
9.8A	479'	Mechanical	Self-Recording	Side-on
B		Mechanical	Self-Recording	Side-on
9.9A	570'	Mechanical	Self-Recording	Side-on
9.10A	715'	Mechanical	Self-Recording	Side-on

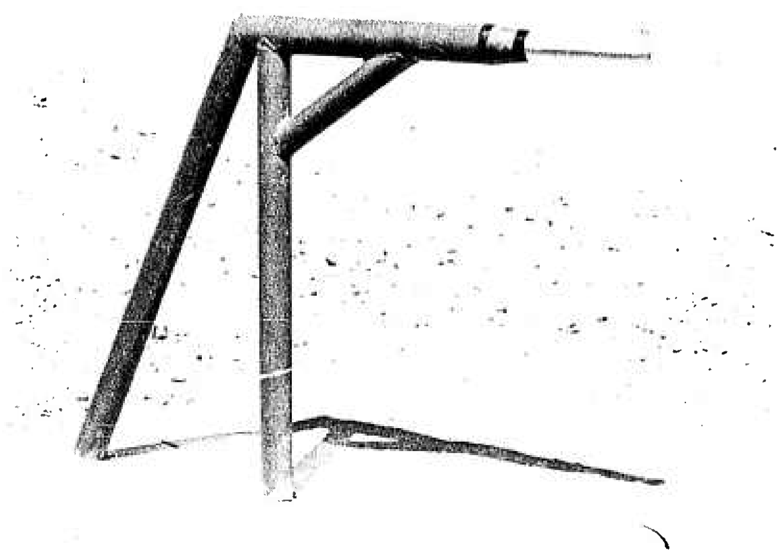

Figure 2.2 Typical Measuring Station

RESULTS

3.1 Overpressure vs Distance

The overpressures recorded by gages located at selected distances from ground zero are listed in Table 3.1. The values listed under maximum overpressure are adjusted values which have been corrected to account for any gain due to overshoot or gage ringing. A linearized plot of the pressure versus time history for each position is presented in the Appendix. The values listed in Tables 3.1 and 3.2 have been plotted in Figure 3.1 versus distance. With the exception of three points all values measured fall well within the $\pm$ 10 per cent error band that is generally expected on field tests of this magnitude. The predicted curve is approximately 2 per cent lower than the measured values along the 200 to 300-foot interval.

3.2 Duration vs Distance

The positive duration of a blast wave is a difficult parameter to measure. This is especially true in the higher pressure region where many transducers lack the ability to follow the pressure decay as it nears the ambient condition. Some piezo gages and recording systems tend to lose the charge developed by the gage and this gives an incorrect duration. Another factor that causes some scatter of points when scaling from one yield charge to another is the appearance of the second shock. At certain distances on some shots the second shock may appear near the end of the positive phase and would indicate a longer duration. At the same scaled distance on a shot of a different yield one may record the second peak at the beginning of the negative phase and the scaled duration would be shorter. The measured durations are listed in Tables 3.1 and 3.2 and are plotted in Figure 3.2 along with the predicted curve.

The measured values are longer than the predicted curve over the 100 to 300-foot interval. It is not suggested here that the curve be shifted on the basis of seven measurements especially in view of the scatter of points over the 250 to 500-foot interval along the blast lines.

TABLE 3.1

Measured Blast Parameters on U. S. Blast Line 7 - 8

Position	Distance from GZ ft	Type Measurement	Maximum Pressure psi	Arrival Time msec	Positive Duration msec	Positive Impulse psi-msec
8.1 B	100	Side-on	380	-	12.0	1818
8.2	120	Side-on	280	11.9	-	1600
A		Side-on	263	-	18.6	1207
B		Side-on	310	-	12.0	1119
8.3 A	140	Side-on	180	-	38.0	-
B		Side-on	175	-	-	-
8.4A	232	Side-on	82	-	84.0	991
8.5	279	Total	106	64.3	115	-
		Side-on	-	-	-	-
A		Side-on	56	-	95	1080
8.6	299	Total	76	73.3	102	-
		Side-on	42	73.3	109	1170
A		Side-on	38.3	-	97	787
8.7	334	Total	56	89.1	98	-
		Side-on	34	89.1	121	818
A		Side-on	30	-	85	642
8.8	413	Total	27	134.4	100	-
		Side-on	30	134.4	117	670
A		Side-on	18.1	-	104	540
8.9	443	Total	24	148.2	117	-
		Side-on	17	148.2	132	560
A		Side-on	15.8	-	121	549
8.10	525	Side-on	11.5	204.4	-	-
A		Side-on	12.3	-	130	465
8.11 A	1020	Side-on	3.9	-	181	265
8.12 A	2800	Side-on	1.0	-	249	98
B		Side-on	1.0	-	247	103

NOTE: All stations with an alphabetical designation A or B are self-recording gage stations.

TABLE 3.2

Measured Blast Parameters on U. S. Blast Line 9

Position	Distance from GZ ft	Type Measurement	Maximum Pressure	Arrival Time	Positive Duration	Positive Impulse
9.3	204	Side-on	105	36.7	75	1114
A*		Side-on	86.4	-	-	-
B*		Side-on	99.5	-	-	-
9.4	261	Total	107	57.5	-	-
		Side-on	58	57.5	107	1014
A*		Side-on	53.6	-	-	-
B*		Side-on	71.6	-	-	-
9.5	301	Total	76	75.8	96	-
		Side-on	35	75.8	94	712
A*		Side-on	38.0	-	-	-
9.6	350	Side-on	29	100.6	93	655
A*		Side-on	30.6	-	-	-
B*		Side-on	27.5	-	-	-
9.7	410	Side-on	20	134.8	120	638
A*		Side-on	24.3	-	-	-
9.8A*	479	Side-on	15.8	-	-	-
B*		Side-on	15.8	-	-	-
9.9A*	570	Side-on	12.8	-	-	-

*NOTE: Initiation circuit failed to close. All measurements are peak pressure only.

All stations with an alphabetical designation A or B are self-recording gage stations.

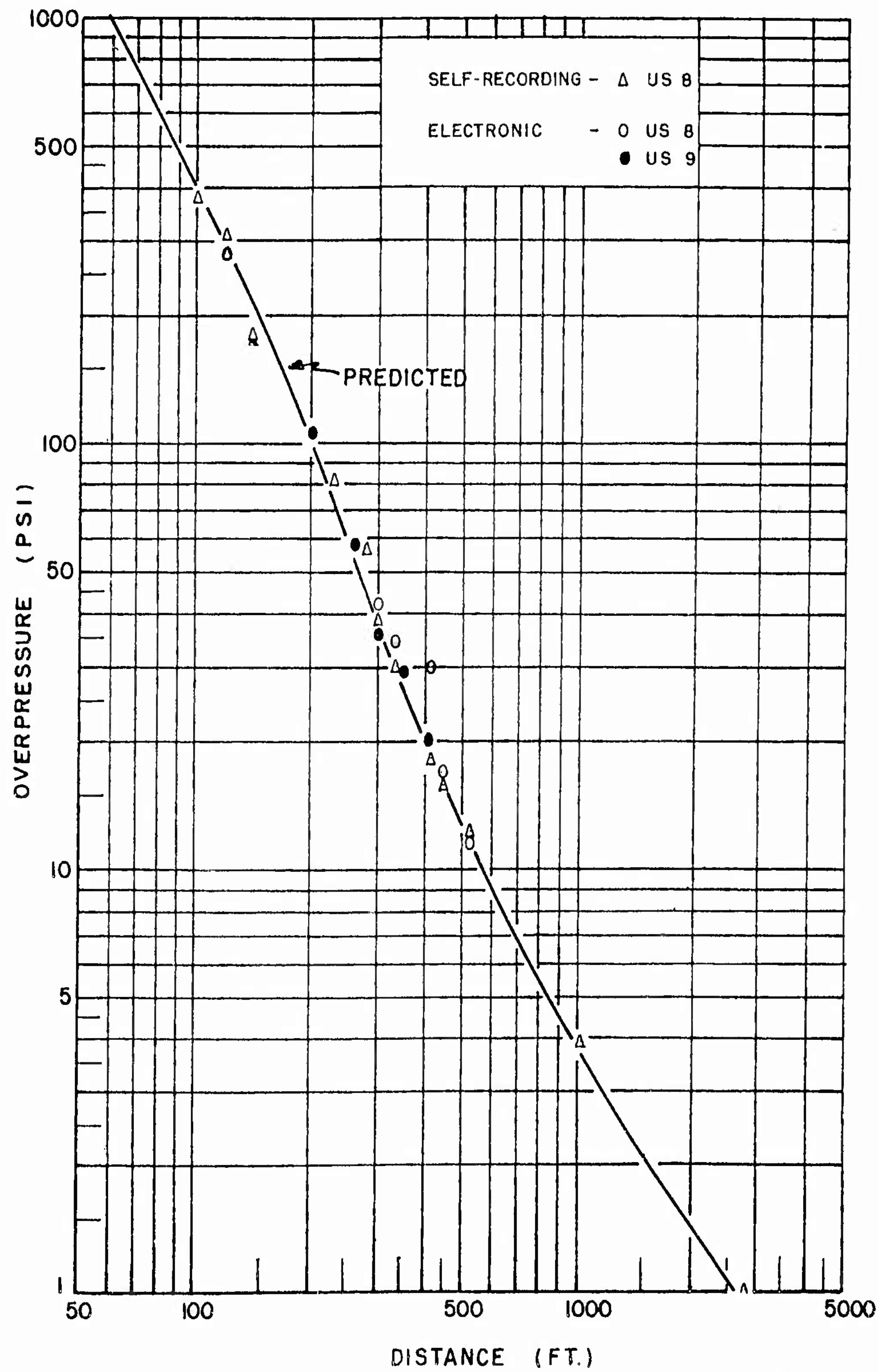

Figure 3.1 Predicted and Measured Overpressure versus Distance for a 100-Ton TNT Surface Burst

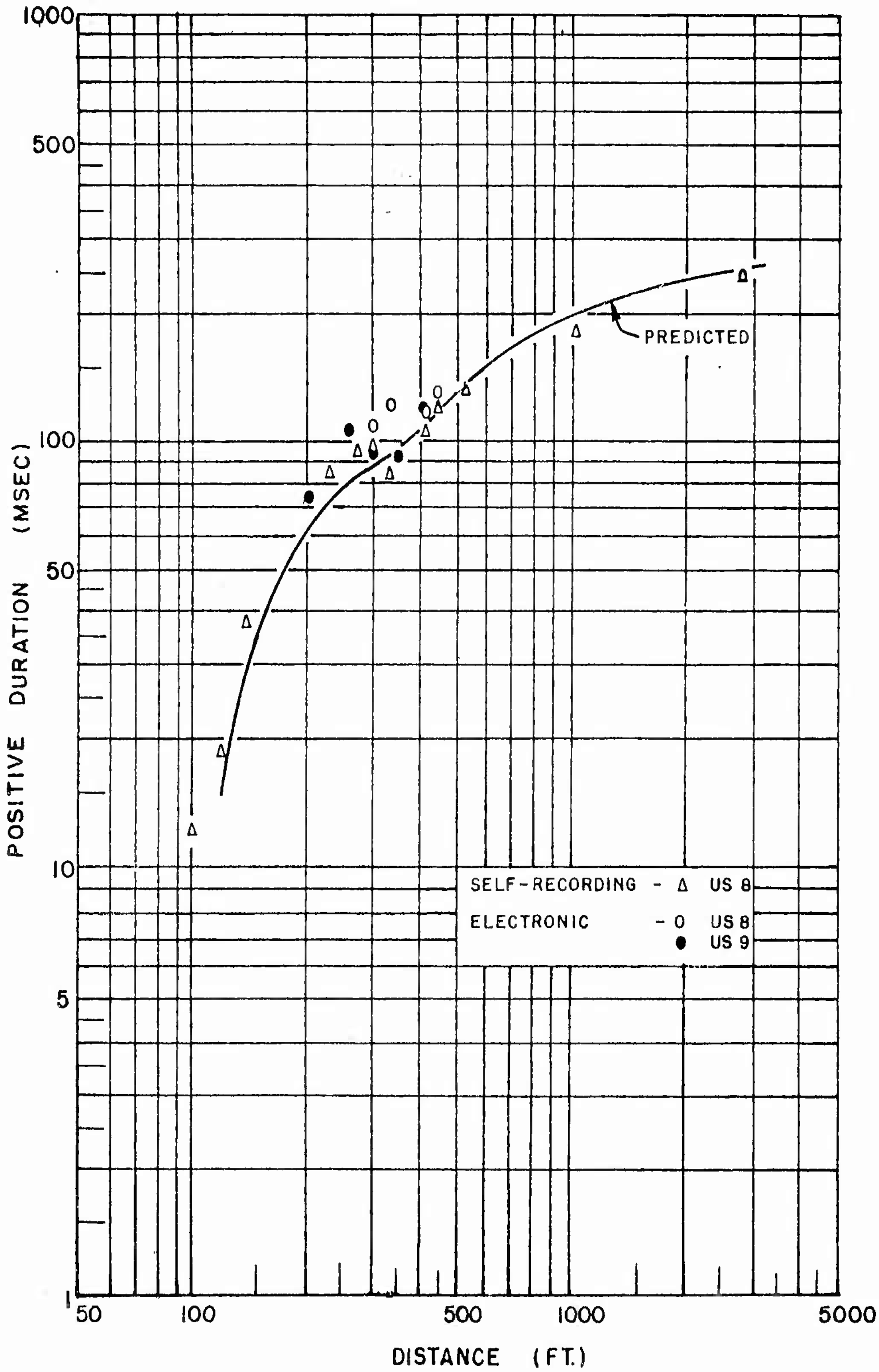

Figure [illegible] Predicted and Measured Positive Duration versus Distance for a 100-Ton TNT Surface Burst

3.3 Impulse vs Distance

Impulse within the positive pressure phase is a blast parameter of growing importance in recent years as a damage criterion. There is usually less scatter in impulse measurements than there is in pressure or duration because a small variation in peak pressure or duration does not affect the area under the curve as much as an individual variation would imply. Impulse values are listed in Tables 3.1 and 3.2 and are plotted in Figure 3.3.

There is more scatter in the impulse measurements than expected and there is a correlation in the ground distance over which the scatter of duration and scatter of impulse occurs. It should also be noted that the impulse measurements are higher than predicted over the same ground range that the overpressure and duration measurements are higher and longer than predicted.

3.4 Arrival Time vs Distance

The time of arrival of the shock wave at given distances can be related to the peak overpressure by determining the shock velocity. The arrival time may be determined through the use of backdrops and high speed photography or through the use of a zero time pulse and noting the arrival time of the shock wave at gage stations along a blast line. Measuring arrival time on different lines will also give a good indication of the symmetry of the blast. The arrival times are listed in Tables 3.1 and 3.2 and plotted in Figure 3.4. Measured arrival times were corrected to compensate for relay closures in the following manner. The delay measured between the time zero closure, supplied by the Canadian firing console, and the true detonation time zero was added to all apparent arrival times. The true detonation time was clearly discernable on the cathode ray recorders because of the pickup of the ionization pulse. This time (3.6 milliseconds) was added to the Leach and Miller recordings. Since an additional relay was used to trigger the Consolidated recorders, its closure time (nominally 1.5 milliseconds)

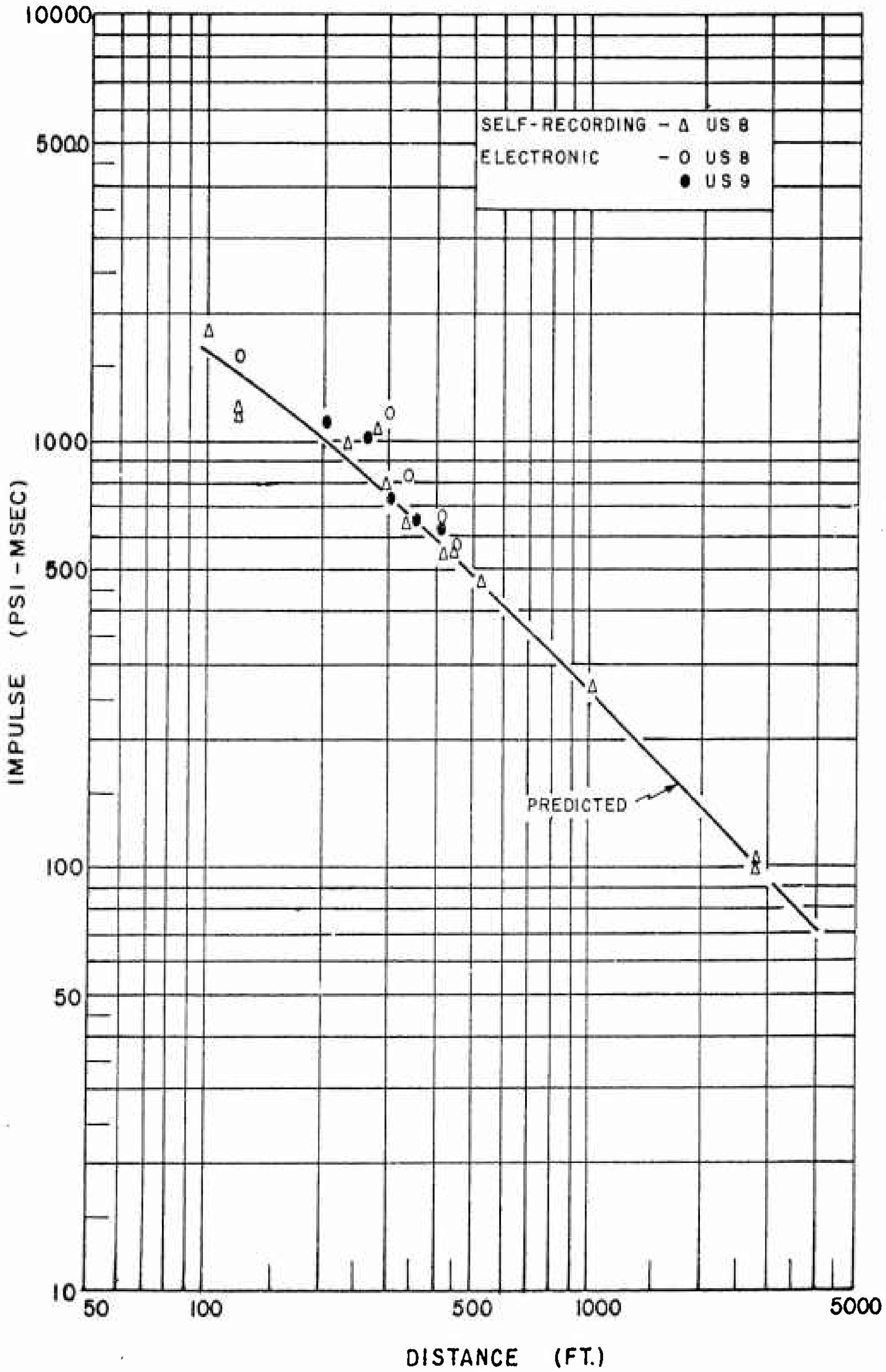

Figure 3.3 Predicted and Measured Positive Impulse versus Distance for a 100-Ton TNT Surface Burst

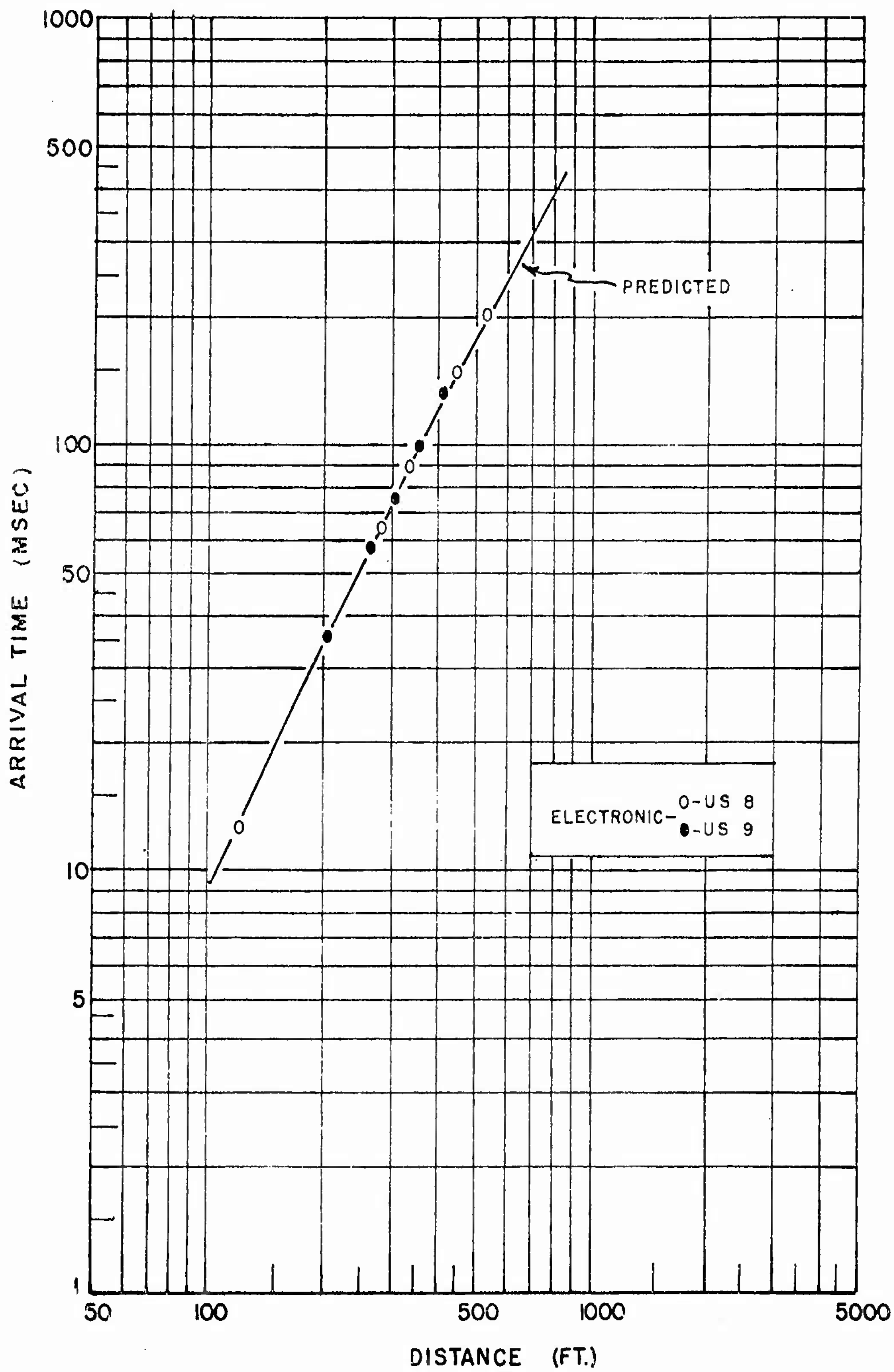

Figure [illegible] Predicted and Measured Arrival Time versus Distance for a 100-Ton TNT Surface Burst.

was added to these recorders making a total lag of 5.1 milliseconds. These corrections are quite critical at the close-in station and become less important at great distances.

The arrival times recorded by the electronic recording systems only are plotted in Figure 3.4. The uncertainty of the amount of lag in the closure of the various timing signal relays and the motor start-up time gave erratic arrival time values for the self-recording gages and therefore they are not plotted in Figure 3.4. The arrival time values recorded along the two blast lines indicate that the shock front was symmetrical around ground zero.

3.5 Dynamic Pressure vs Distance

The dynamic pressure versus distance is one of the most important blast parameters associated with the damage mechanism of drag sensitive targets. The dynamic pressure as presented in this report is not a direct measurement but is calculated from a side-on measurement made flush with the ground surface and a corrected total head measurement made at three feet above the surface. The total head correction is a function of the Mach number of the flow behind the shock front and can be obtained from the following relationship:

$$\frac{P'_t}{P'_s} = \left[1 + \frac{\gamma-1}{2} M^2\right]^{\frac{\gamma}{\alpha-1}} \quad \text{for } M < 1 \quad \text{and}$$

$$\frac{P'_p}{P'_s} = \left[\frac{\left(\frac{\gamma+1}{2} M^2\right)^{\gamma}}{\left(\frac{2\gamma}{\gamma+1} M^2 - \frac{\gamma - 1}{\gamma + 1}\right)}\right]^{\left(\frac{1}{\gamma - 1}\right)} \quad \text{for } M > 1 .$$

When the Mach numbers are calculated from one of the above equations they are used to determine the necessary correction for the as-read total head measurements from established calibration curves. The corrected total

head values are then used to calculate new Mach numbers. At this point it would seem that the dynamic pressure probe is not used so much to determine dynamic pressure as it is to determine the Mach number of the flow; for knowing the value of the Mach number (M) and the side-on static overpressure (ΔP), and assuming a value for $\gamma = 1.4$ for air, the dynamic pressure can be found immediately from the following relationship:

$$q = \frac{\gamma (\Delta P) M^2}{2} .$$

This process was used to obtain the final dynamic pressure values plotted in Figure 3.5.

The predicted dynamic pressure curve as plotted in Figure 3.5 was calculated from the following relationship:

$$q = \frac{2.5 (\Delta P)^2}{7P_o + (\Delta P)} .$$

The values of ΔP were obtained from the predicted overpressure curve plotted in Figure 3.1. As can be seen from Figure 3.5 good agreement was obtained between the "measured" and predicted values of dynamic pressure.

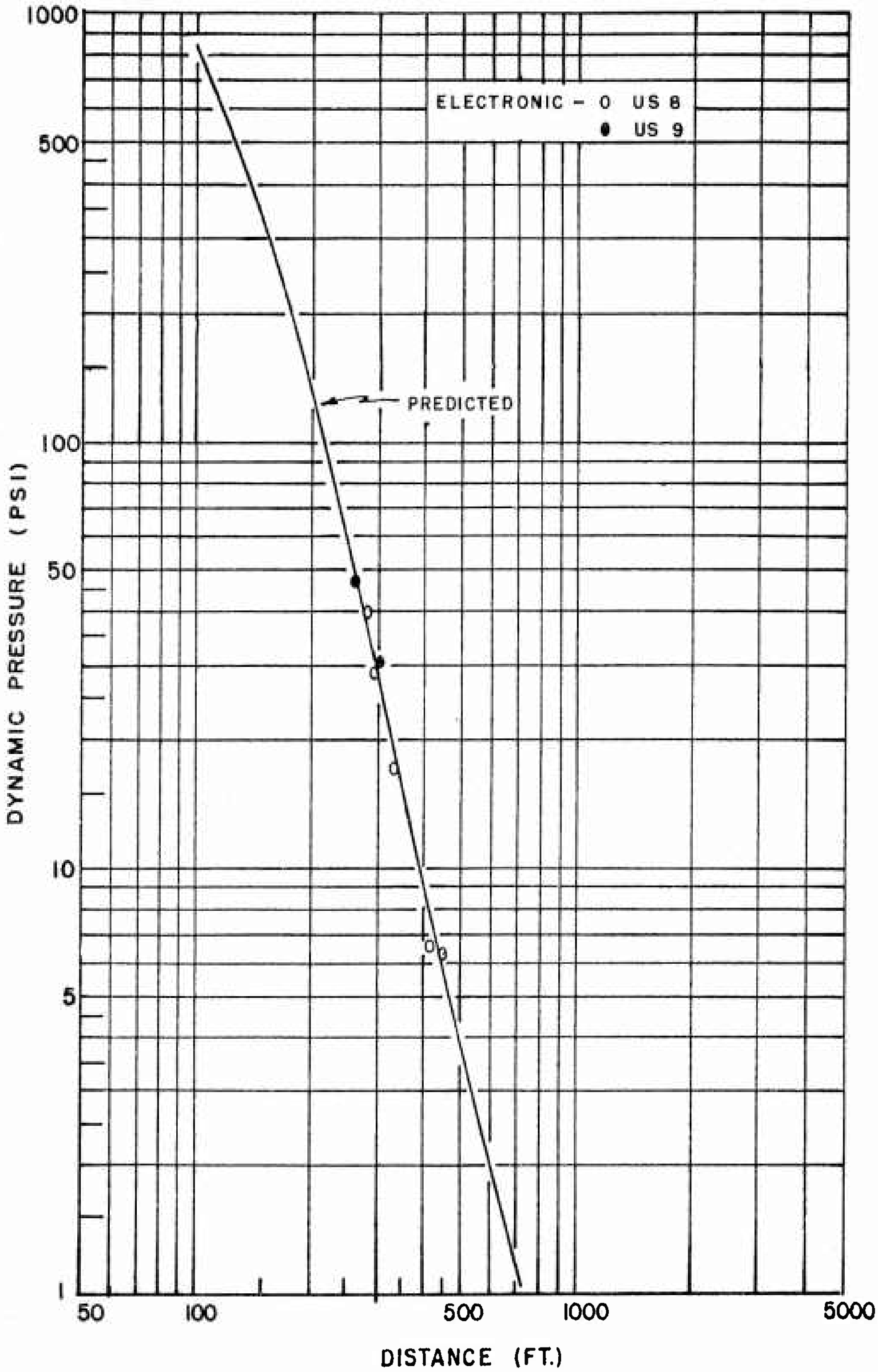

Figure 3.5 Predicted and Measured Dynamic Pressure versus Distance for a 100-Ton TNT Surface Burst

DISCUSSION AND CONCLUSIONS

4.1 Results from Blast Line Number 8

Blast line number 8 ran between the tunnel project (US-7) and the topography project (US-8). The station numbers and distances are shown in Figure 2.1. The results from the various recorders have been plotted in the form of overpressure versus time and are presented in an Appendix to this report. At stations where more than one gage or method of recording was used, all records obtained have been plotted on the same paper for comparison. The overpressure versus time records at levels below 100 psi are felt to be quite reliable with but two exceptions. One being the decay rate in the latter portion of the electronic record at station 8.6 and the second one being the peak overpressure recorded on the electronic system at station 8.8.

At overpressures greater than 100 psi it is felt that the reliability in the positive duration and overpressure measurements is not as good as it is in the lower pressure region. The record obtained at station 8.1 appears satisfactory for positive duration although the overpressure is low because of gage response time. At station 8.2 there appears to be a strange phenomenon occurring where the pressure goes negative at about three milliseconds. No reason has been determined to disbelieve the gage record. There is some hysteresis in the transducer which does not allow it to return to ambient pressure as the blast wave returns. The two self-recording gages at this station show some acceleration effects although the positive durations are reasonable. At station 8.3, both records are poor for any wave shape analysis. The peak overpressures are low and the positive duration of recorder B is much too long.

4.2 Results from Blast Line Number 9

Blast line number 9 ran between US-8 and the jeep project (US-9). On D-1 an earth mover severed one of the timing signal lines going to the main relay starter box for the self-recording gages. The gages did not receive a signal and only peak overpressure was recorded. The electronic

recording system operated satisfactorily and the records from all but the first two stations are considered reliable. Station 9.3 and 9.4 both record some overshoot on the initial rise and at station 9.3 there was also some objectional oscillation recorded which is believed to be either acceleration effects or gage ringing.

4.3 General Conclusions

The overall free-field measurements of overpressure versus time at selected distances from ground zero were successful. The overpressure values measured along the blast line validate the cube-root scaling laws up to 100 tons of TNT. The values of positive duration deviate slightly from the predicated curve, although the larger deviations are from records where the interpretation of duration is difficult and sometimes questionable. The positive impulse measurements compare favorably with the predicated curve, with the exception of a few values between 250 feet and 450 feet from ground zero. This is the distance over which the scatter in positive duration occurs. The arrival times are quite reliable and both lines fall on the predicted curve, indicating good symmetry of the blast wave. The measured peak dynamic pressure values compare favorably with the predicted values over the ground distances instrumented.

C. N. Kingery
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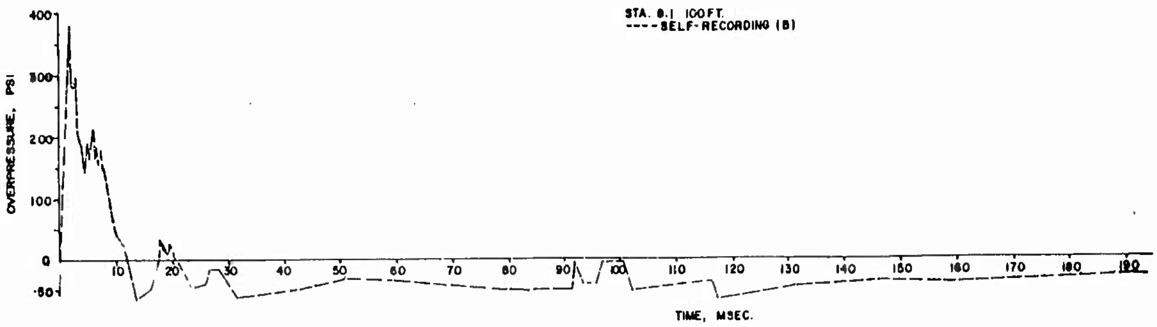
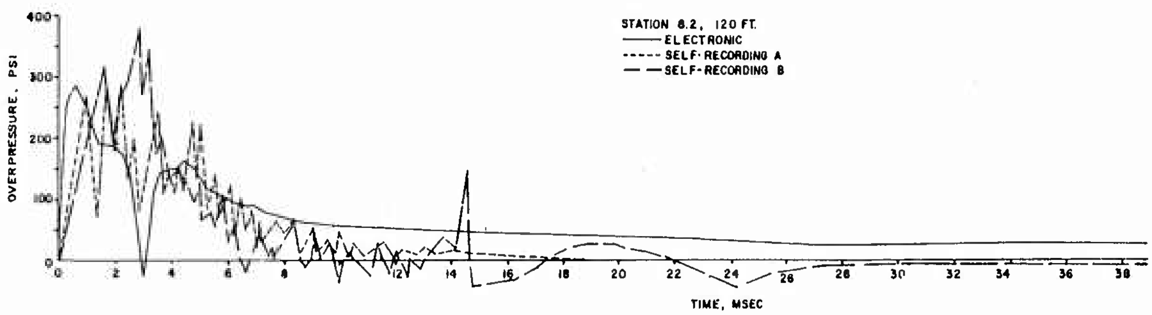
J. H. KEEFER

J. D. Day
J. D. DAY

APPENDIX

RECORDS OF PRESSURE VERSUS TIME


STA. 8.1 100 FT.
----SELF-RECORDING (B)
OVERPRESSURE, PSI
TIME, MSEC.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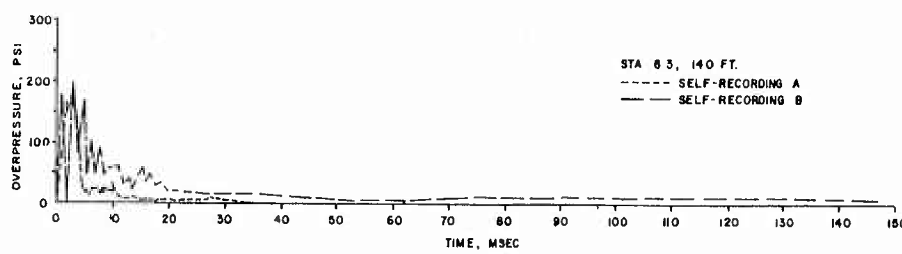
-----SELF-RECORDING A
— —SELF-RECORDING B
OVERPRESSURE, PSI
TIME, MSEC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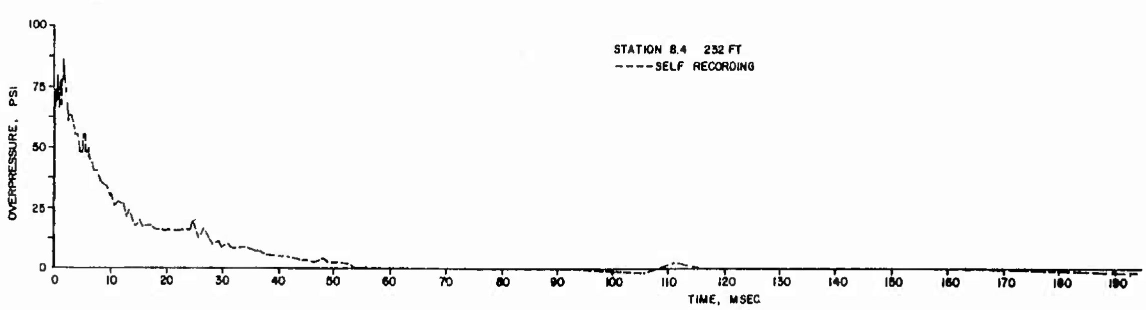
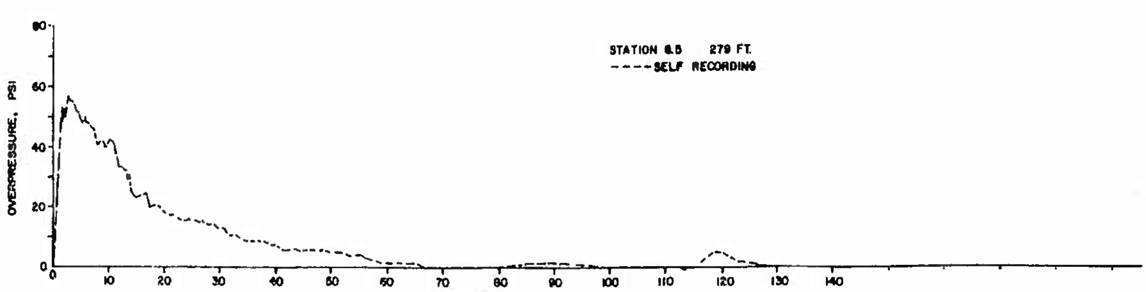
— — SELF-RECORDING B
OVERPRESSURE, PSI
TIME, MSEC


STATION 8.4 232 FT
----SELF RECORDING
OVERPRESSURE, PSI
TIME, MSEC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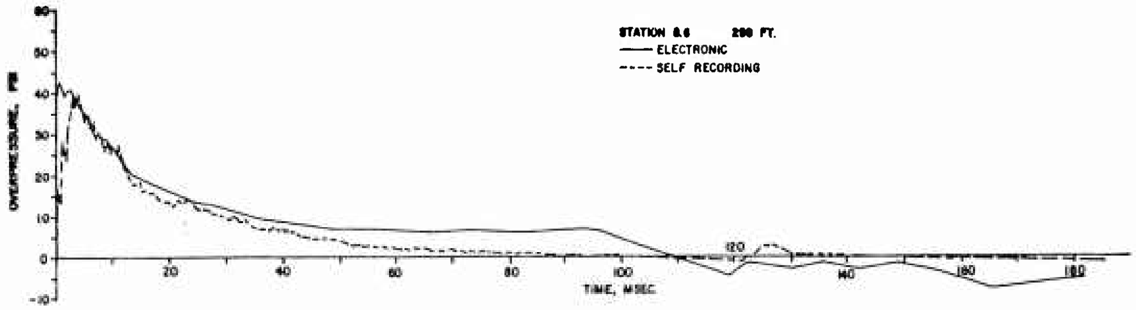
OVERPRESSURE, PSI
TIME, MSEC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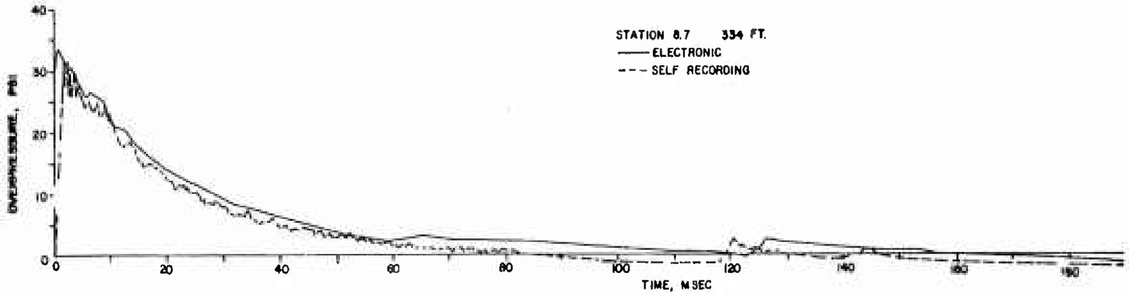
SELF RECORDING
OVERPRESSURE, PSI
TIME, MSEC.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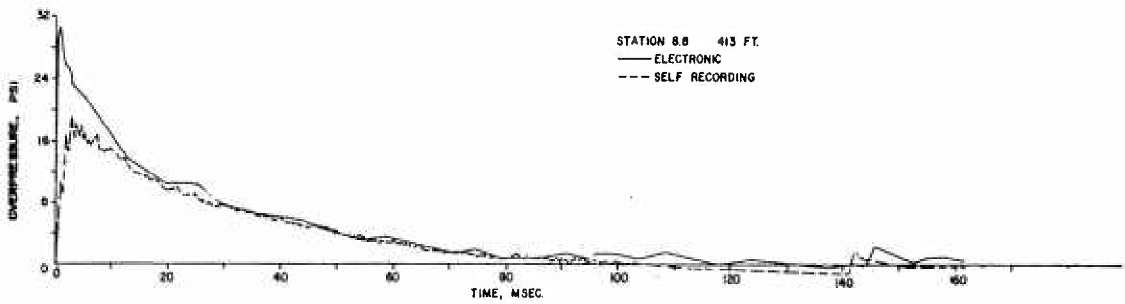
SELF RECORDING
OVERPRESSURE, PSI
TIME, MSEC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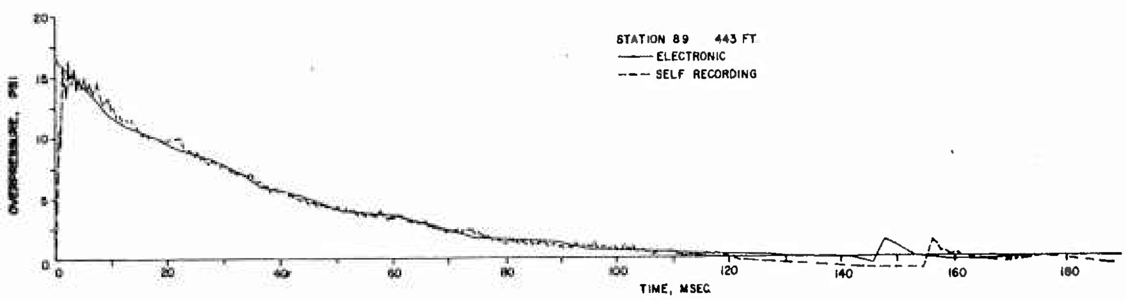
SELF RECORDING
OVERPRESSURE, PSI
TIME, MSEC.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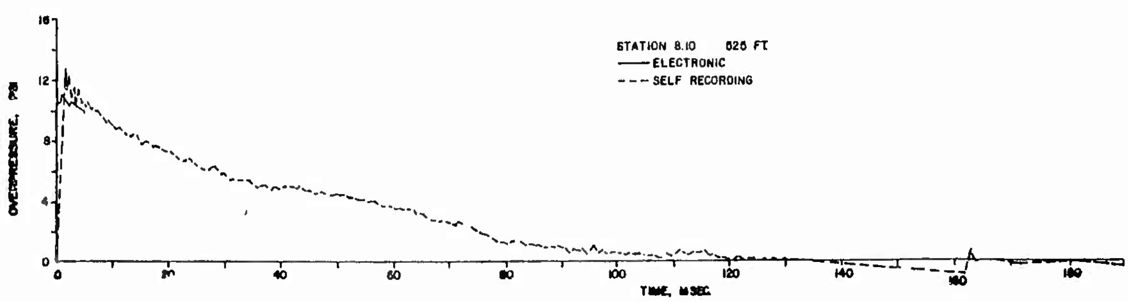
SELF RECORDING
OVERPRESSURE, PSI
TIME, MSEC.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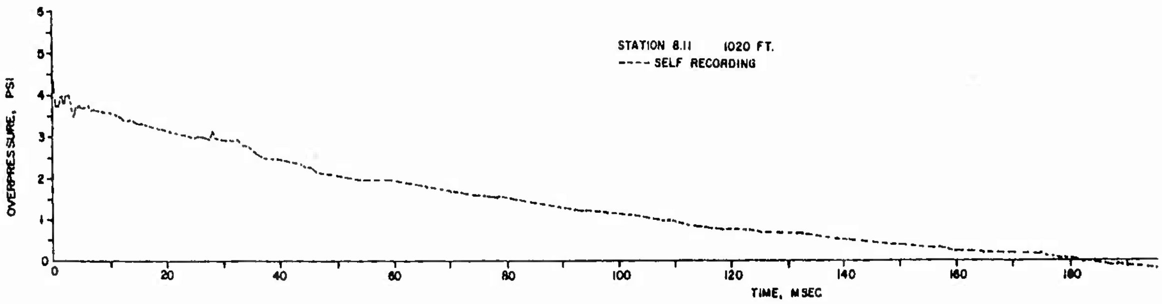
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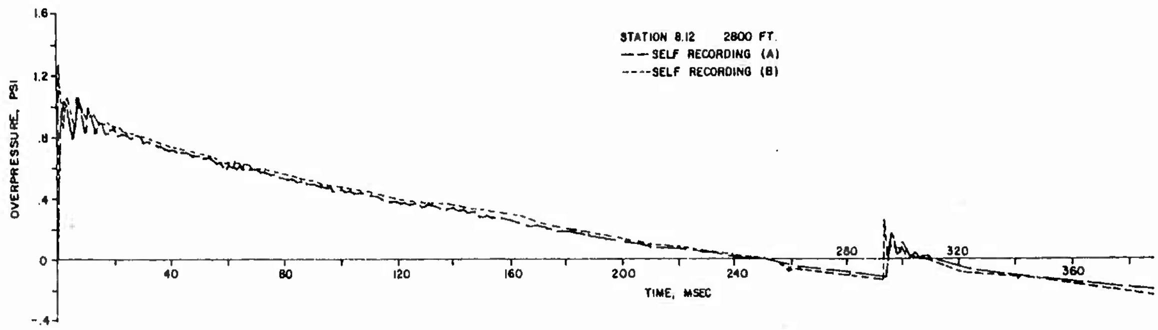
TIME, MSEC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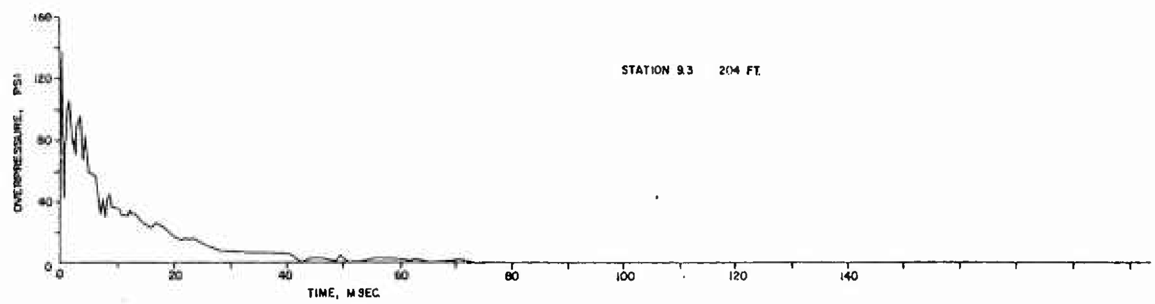
OVERPRESSURE, PSI
TIME, MSEC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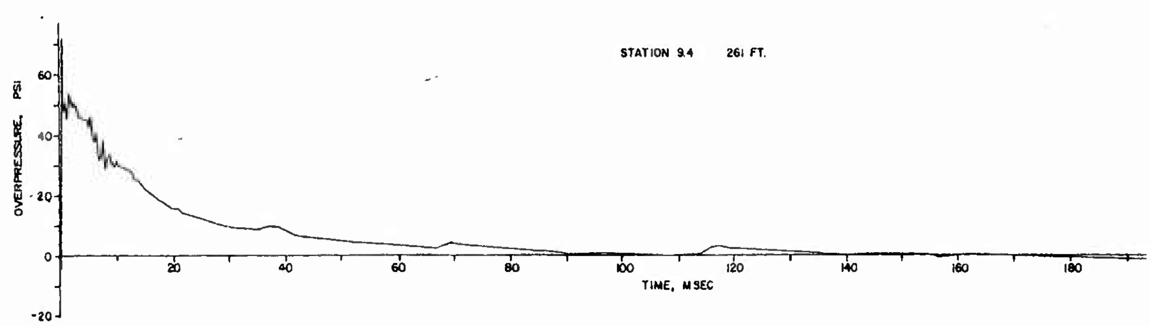
TIME, MSEC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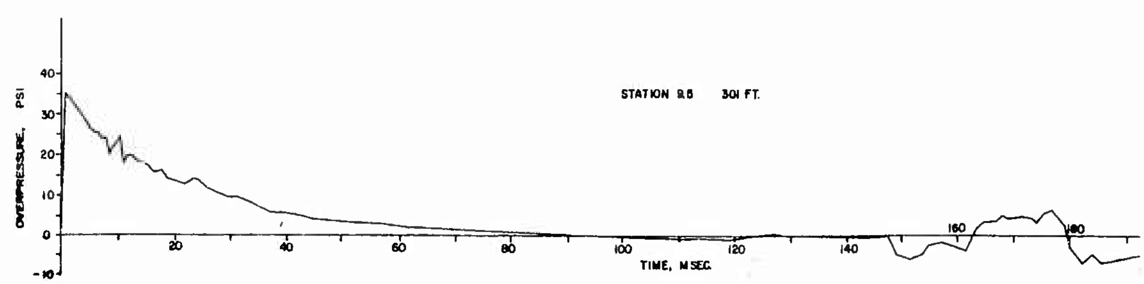
TIME, MSEC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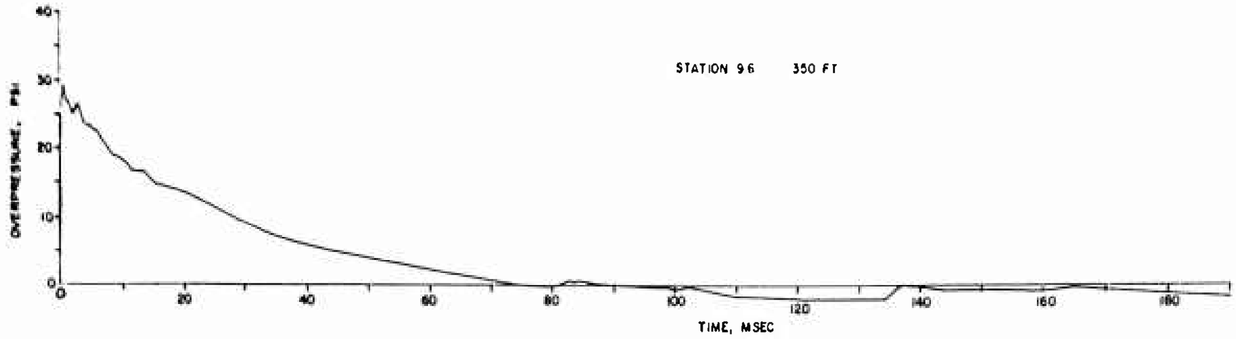
TIME, MSEC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TIME, MSEC
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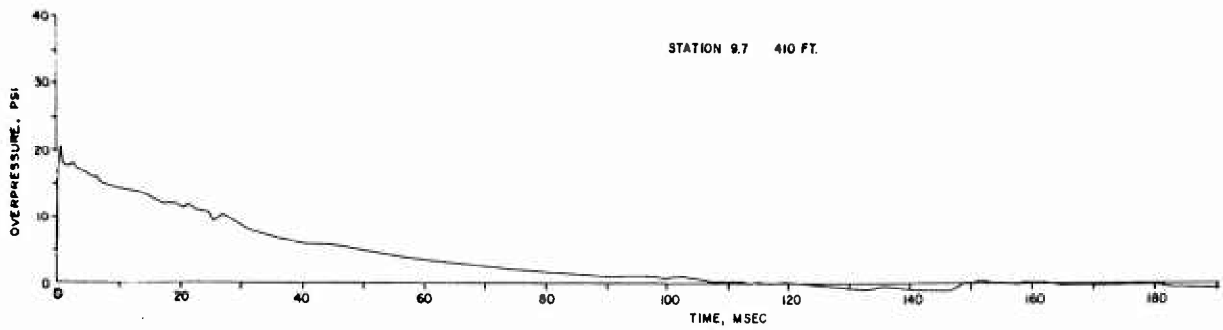
180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TIME, MSEC
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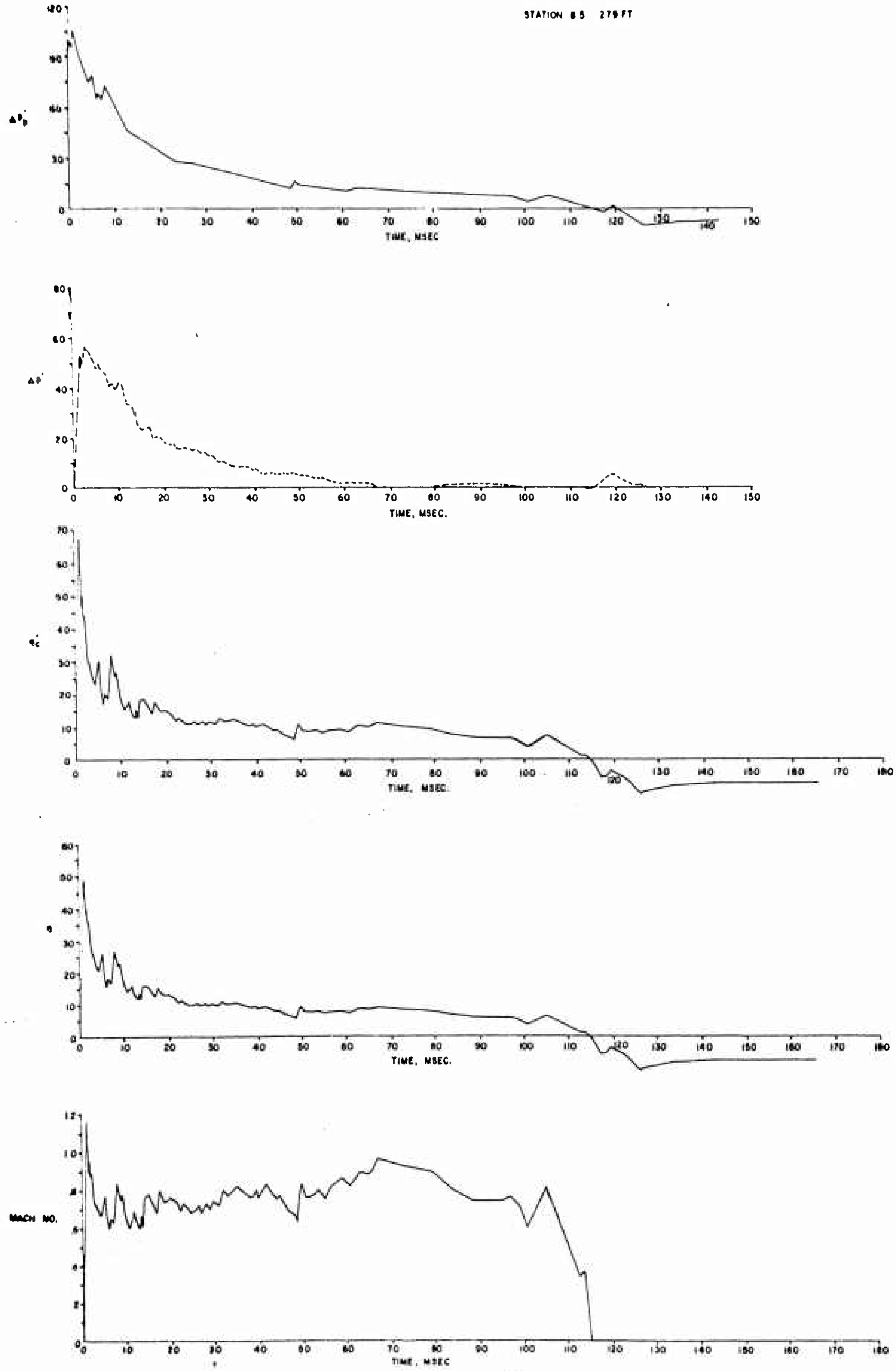
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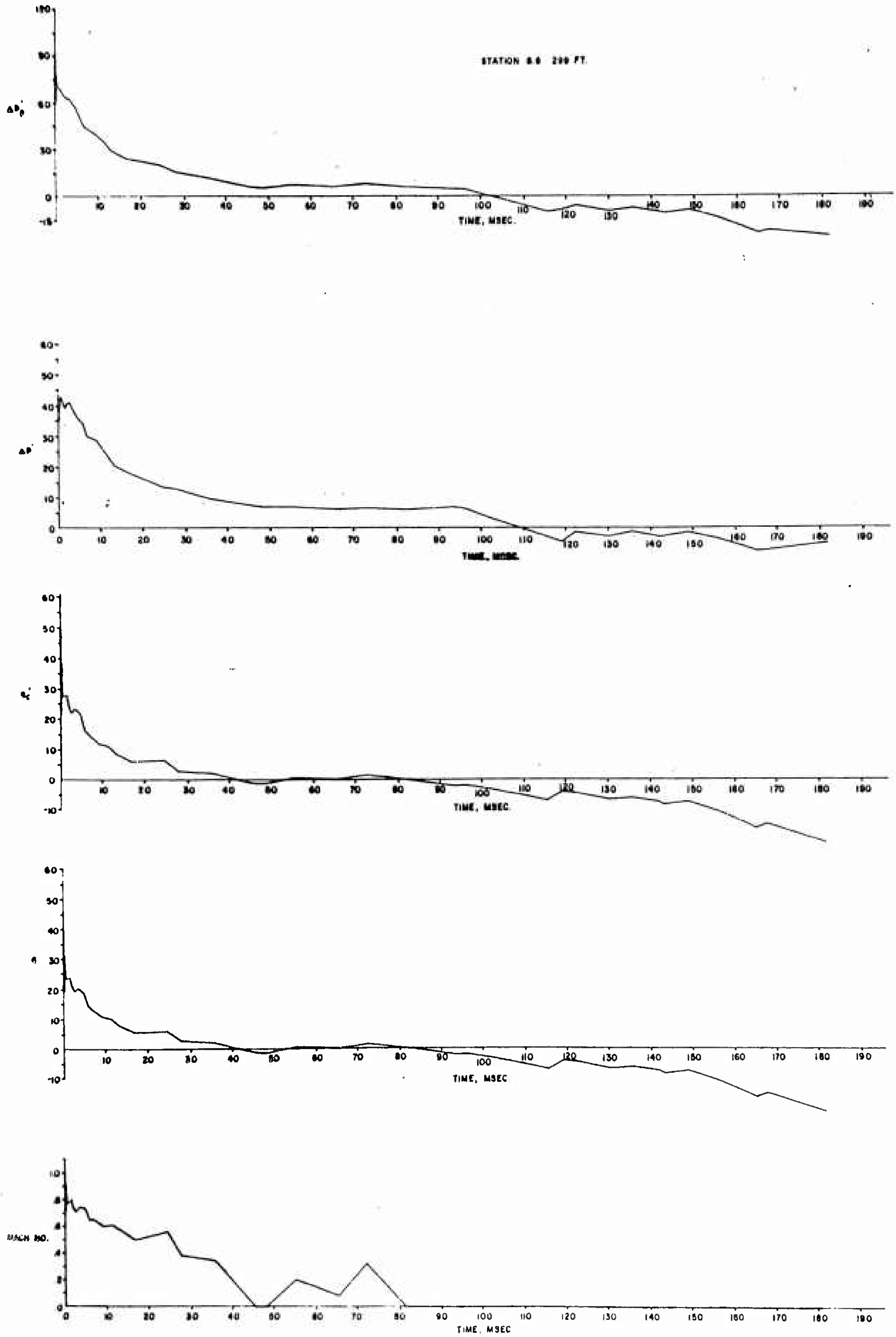
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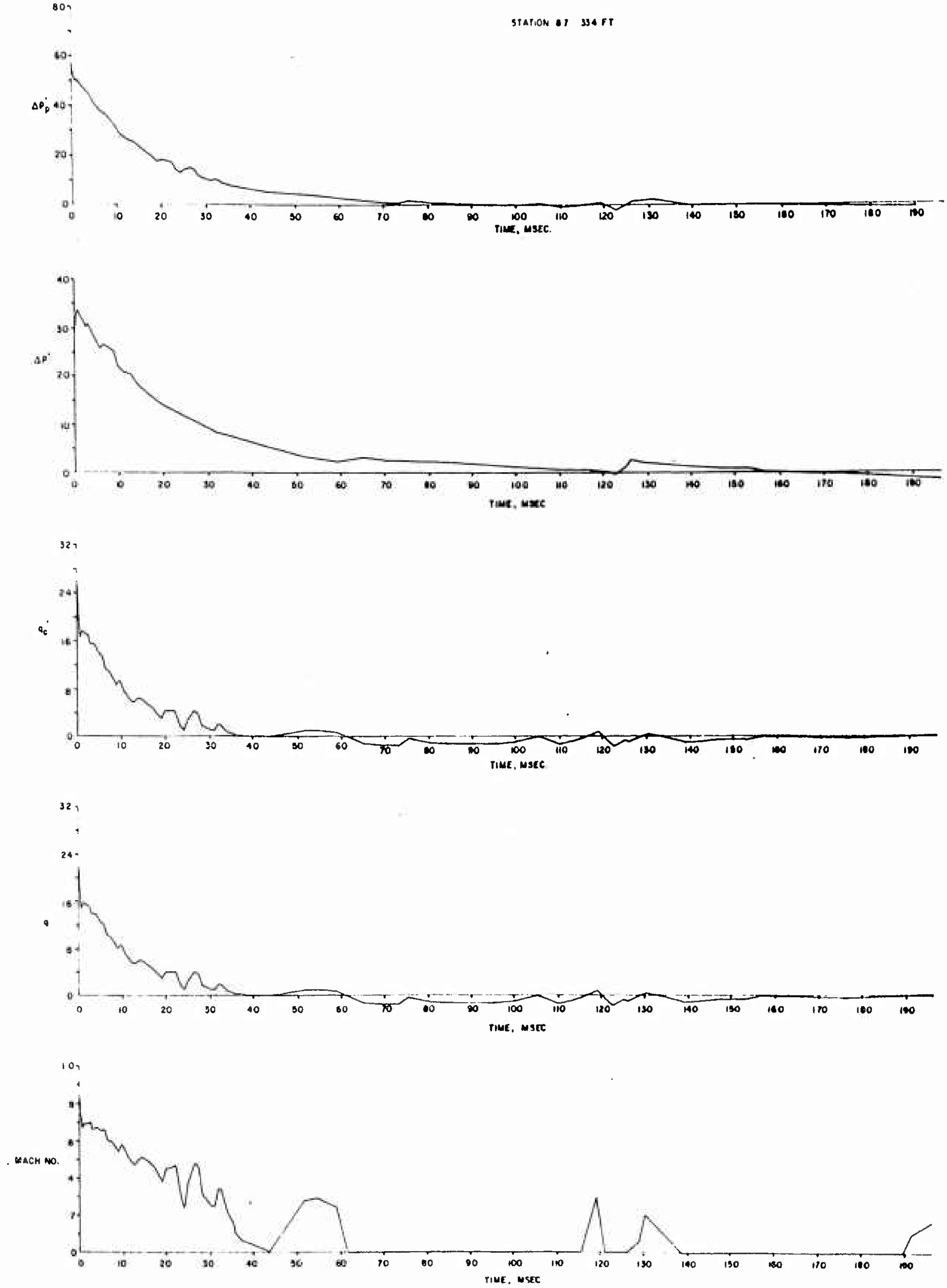
TIME, MSEC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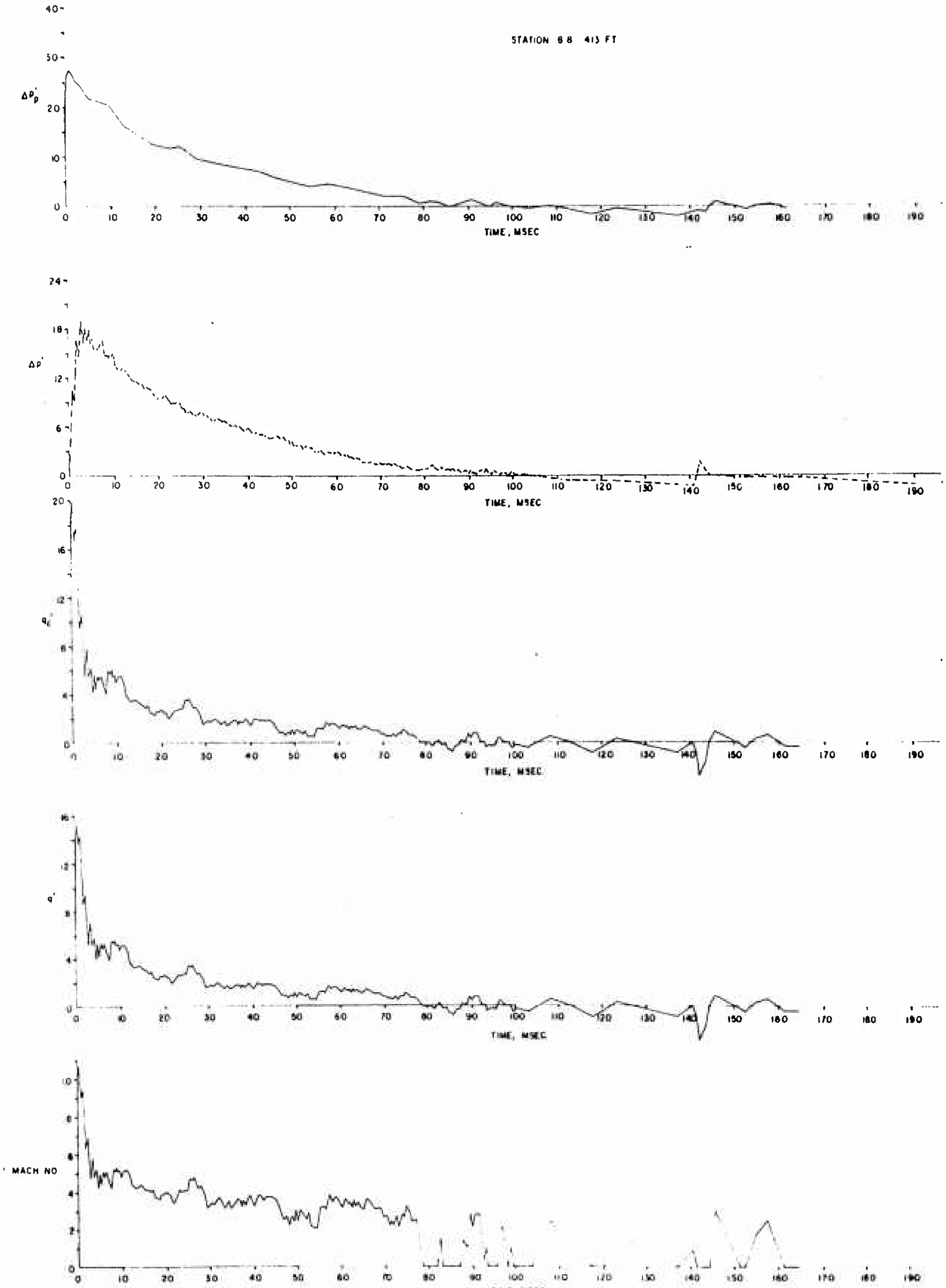
ΔP'p
ΔP'
q'c
q
MACH NO.
TIME, MSEC.



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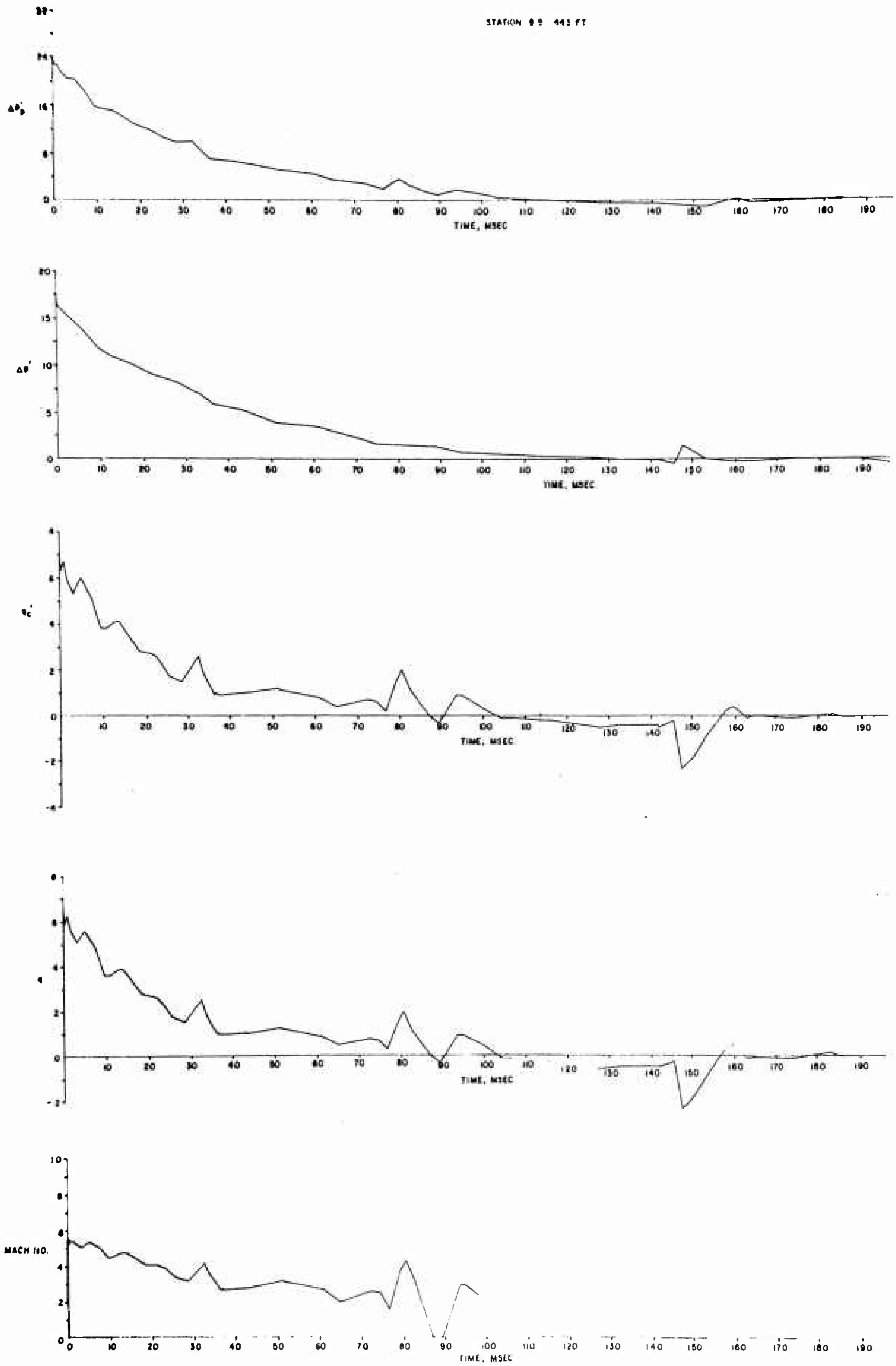
TIME MSEC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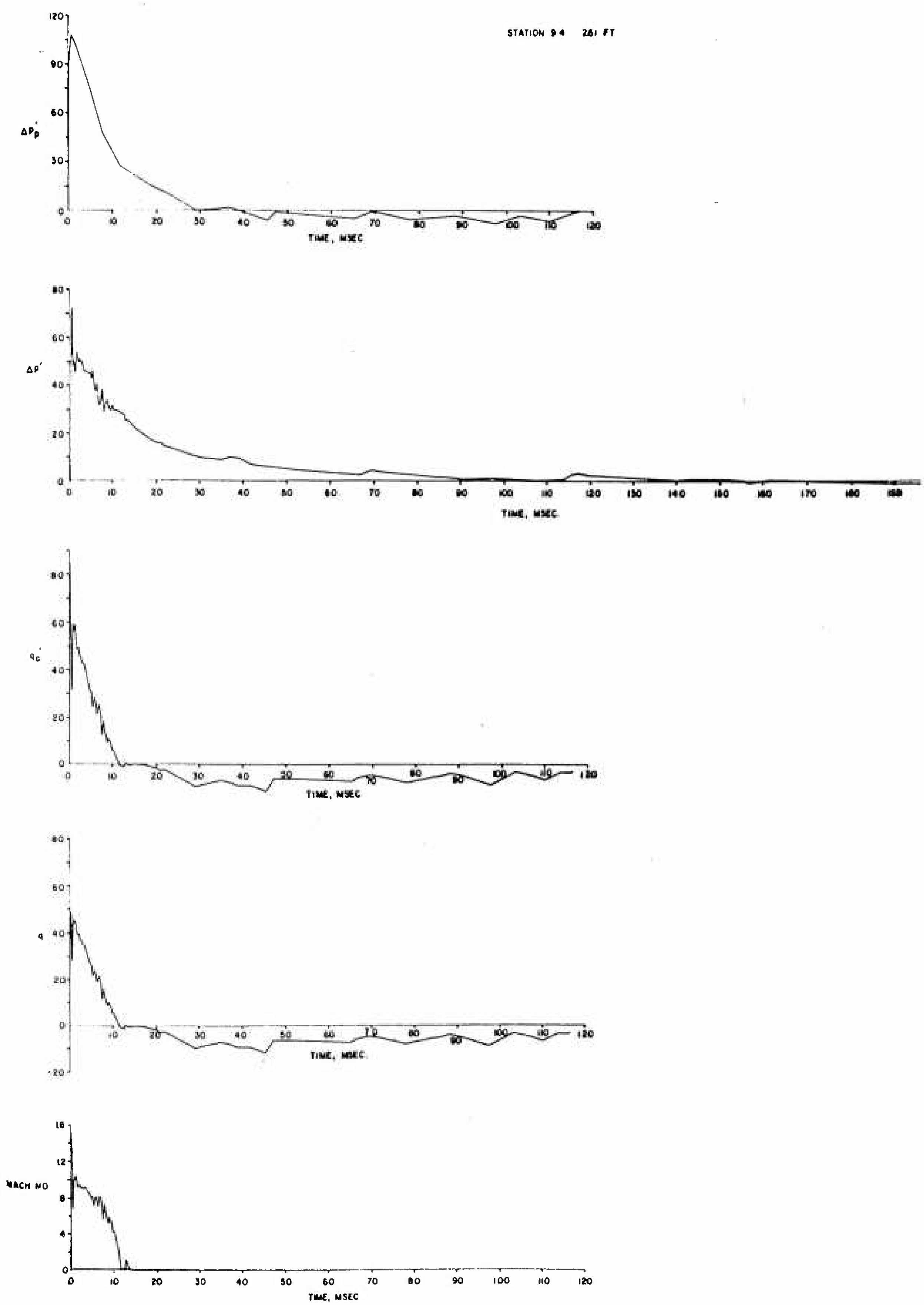
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ΔP'
q'c
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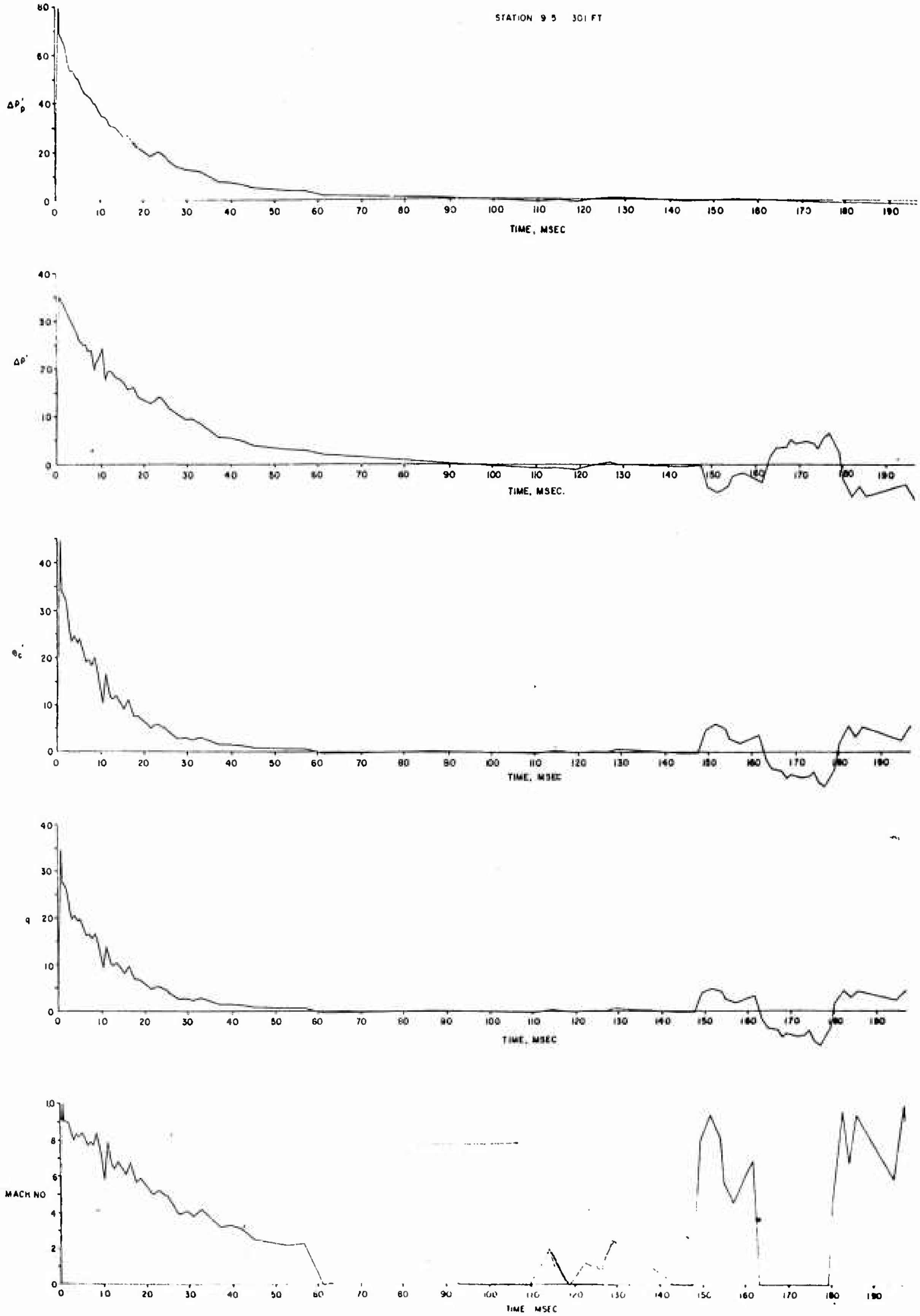
TIME, MSEC


STATION 9.5 301 FT
$\Delta P_p'$
$\Delta P'$
e_c'
q
MACH NO
TIME, MSEC

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Blast effects - Measurements
Trinitrotoluene - Blast

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